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STATUS REPORT OF THE RD-8 COLLABORATION

The GaAs Collaboration

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1 Introduction

The main objectives of the collaboration are: -

- fabrication and testing of simple GaAs detectors for charged particles and X-rays
- understanding of the properties and limitations of these simple, pad detectors
- investigation of alternative wafer materials and detector fabrication technologies
- fabrication and testing of prototype microstrip detectors to LHC specifications
- demonstration of the radiation-hardness of GaAs detectors and understanding its limitations
- encouraging the commercial production of GaAs microstrip detectors
- developing a detailed understanding of the costs of commercial detectors
- design, fabrication and testing of GaAs pixel detectors

In addition to work carried out in pursuit of these goals, progress has been made in the understanding of charge transport and trapping in GaAs and of the apparent variability of performance of our first microstrip detectors, using a wide range of experimental techniques. Monte Carlo models of GaAs detectors, based on this improved understanding, are now able to give a reasonably complete prediction of their response to various sources of ionising radiation. We believe that GaAs detectors are now a credible option for applications in the hostile radiation environment of the proposed Large Hadron Collider and also for a wide variety of applications outside of High Energy Physics.

2 Material Issues

The industry standard GaAs substrate wafers are generally prepared from LEC (Liquid Encapsulated Czochralski) crystal growth or using the Horizontal or Vertical Bridgman (HB or VB/VGF) growth techniques. The material in each case is a much poorer semiconductor than is achievable in silicon, containing relatively large concentrations of charge trapping centres which can have severe effects on the properties of charged particle detectors. The typically high resistivity of the material is the result of a compensation mechanism between mid-bandgap traps and shallow acceptor levels due to impurities typically present in the standard crystal growth environment. The collaboration has evaluated material from a range of suppliers of semi-insulating LEC wafers, (MCP, Wacker/Freiberger, Sumitomo, Nippon, AXT,Outukumpu), and compared wafers subjected to a range of annealing techniques which are reported to vary the concentrations of charge trapping centres. The search for an optimum material is ongoing.

In a search for purer GaAs, the collaboration has investigated the potential of epitaxially-grown GaAs layers, deposited on standard substrate wafers by Liquid-phase, Vapour-phase or Molecular Beam epitaxial growth techniques, (LPE, VPE or MBE, respectively). In each case, high purity growth resulting in charge carrier concentrations of $< 10^{14}/cm^3$ is achievable. It is difficult to reach this quality in the layer thicknesses of $100\mu m$ or more desirable for high energy physics applications, and the costs at present seem unrealistically high for large area fabrication. Within the collaboration, efforts are being made to find ways of reducing these costs without unduly compromising the material quality. There is little doubt that epitaxial material would be the material of choice for particle detectors if the correct cost/quality balance could be achieved.

3 Charge Transport and Collection in Simple Pad Detectors

3.1 Charge Collection

Early GaAs detectors fabricated on semi-insulating LEC substrate material suffered from incomplete collection of the charge released by traversing ionising particles [1]. It appears that the poor charge collection efficiency may be correlated with surface effects and with the material dielectric relaxation time [2]. As a result of careful attention to surface finishing of the wafers on which the detectors are fabricated, however, the charge collection efficiency in all of a recent sample of 80 simple pad detectors made in Glasgow is now at least 70%. The ANSTO group continues to pursue an alternative route to improving the surface quality through passivation with atomic hydrogen [3], and the Bologna group has recently investigated the effect of ion implantation as an alternative to the usual contact preparation, with some success. The Sheffield group [4] continues to develop *p-i-n* detectors as yet another alternative to the Schottky diode approach used elsewhere in the collaboration. The eventual choice of fabrication technology will clearly depend on the level and consistency of performance obtained in each case and, of course, on cost.
In any case, a charge collection efficiency consistently at the level of 80% or above seems to be attainable using standard semi-insulating substrate wafers. The corresponding charge signal from a 200 micron thick GaAs detector would then correspond to that from a 300 micron thick silicon detector. Corresponding performance from microstrip detectors is the next step towards reliable production of acceptable, LHC-compatible detectors. Results from very recent test beam runs suggest that this should also be achievable.

Investigations have been made of the electric field distribution through the thickness of sample detectors, using scanning electron microscopy [5], near-band-gap photo-absorption and voltage profiling [6], OBIC (Optical Beam Induced Current) [7], (cf. Fig.1), and proton microprobe methods [8]. Studies have also been made of the response to proton beams of 1 - 6 MeV in energy [9, 10], corresponding to penetration depths into the GaAs of up to 200 microns. The detailed analysis of current pulse shapes from alpha-particles in simple detectors, carried out in Lancaster [11] and in ANSTO [12], has also been used to provide information on trapping in the GaAs substrate. Detailed characterisation of wafer material and contacts have been carried out by the Freiburg group [13] using a range of experimental techniques including admittance spectroscopy, infrared absorption, PICTS and Rutherford backscattering as well as standard I-V, C-V and Hall effect measurements. A summary of some of their results is given in Table 1 and in Fig.6.

Taken together, these experiments provide support for a model [14, 15, 18] in which the electric field is relatively uniform through a "high field" fraction of the wafer thickness and falls to rather low values for the remainder, (cf. Fig.2). In the first region, which increases roughly linearly in thickness with reverse bias voltage, as measured from OBIC, X-ray detection rates and response to minimum ionising particles [16], (cf. Fig.3), the charge collection efficiency is high. In the remaining, "low field" region the field is not capable of sweeping out the electron-hole pairs released by ionising radiation. Detectors of 200 microns thickness become sensitive throughout their entire depth for bias voltages around 200 V (cf. Figure 4).

3.2 Monte Carlo Modelling of Charge Transport

The most successful attempt to model the behaviour of GaAs particle detectors based on Schottky barrier diode fabrication technology has been proposed by Toporowsky *et al* [14, 15], based on earlier work by McGregor et al [17]. Figure 2 shows the electric field distribution predicted by this model and Figures 5 the predicted and measured Landau distributions due to m.i.p.'s for a range of detector bias voltages. The experimentally-measured electric field distribution is in reasonable agreement with the model predictions, as discussed above.

Attempts to understand the above behaviour in terms of the energy levels and concentrations of electron

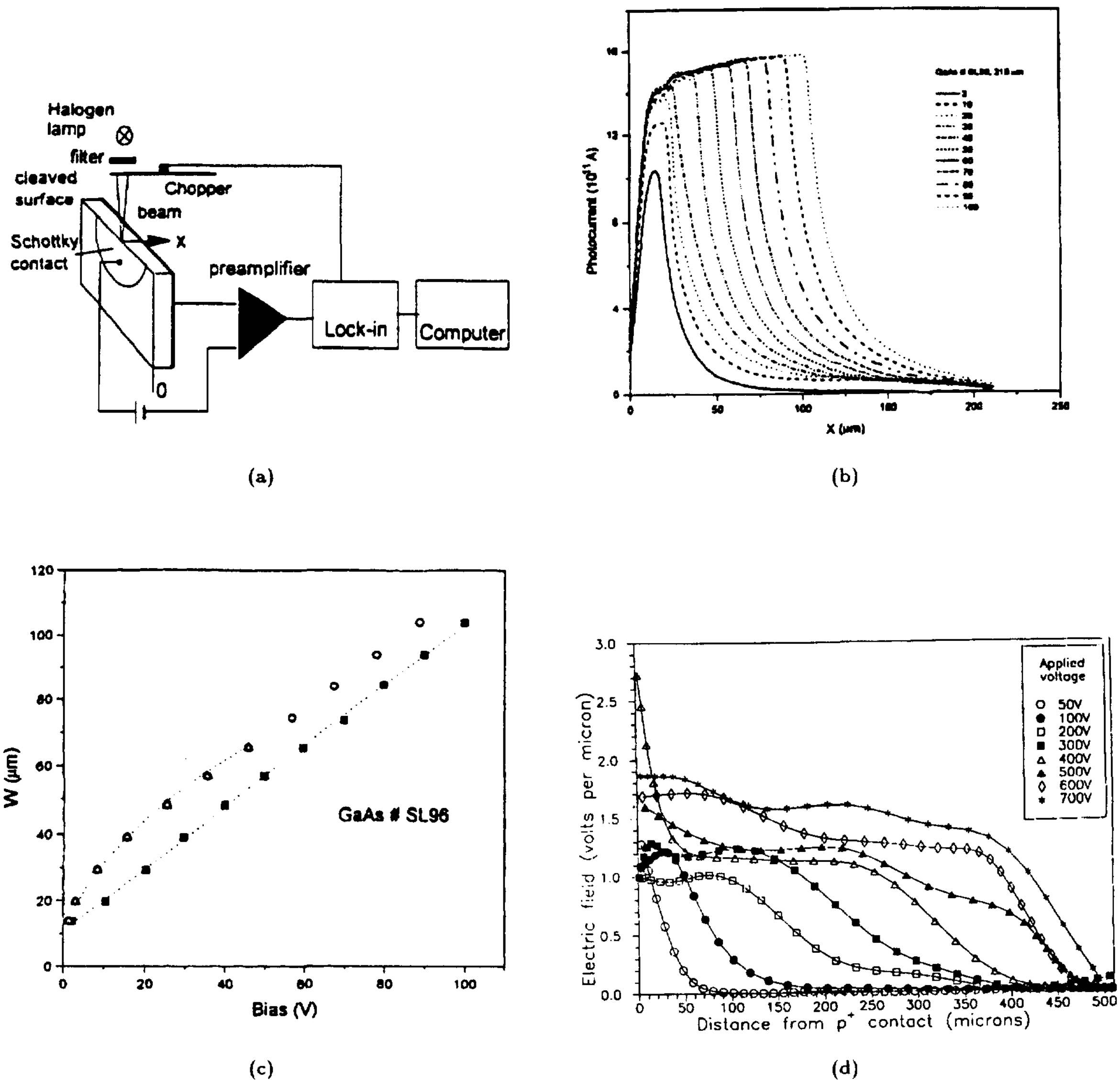


Figure 1: Electric field profiles across the thickness of S.I. GaAs Schottky detectors; (a-c) using a photon beam, (d) by direct voltage probing

Wafer	Orientation	Hall $\mu[cm^2/Vs]$	Hall $\rho[10^7 \Omega\ cm]$	Admittance $\lambda E[eV]$	IR-Measurement $N_{DD} 10^{16} cm^{-3}]$	CV-Measurement $N_{DD} 10^{15} cm^{-3}]$	I-U Measurement $j_L[nA/mm^2](-200V)$	α-Spectrum C.C.E.[%](-200V)
MCP 2266/3	(100)	5488	4.3	0.23 0.4 0.67 0.74	1.80	2.63	30.2	35
MCP 2266/52	(100)	6000	1.4	0.26 0.54 0.73	1.55	3.32	17.1	22
MCP 2266/102	(100)	5700	3.9	0.35 0.6 0.69 0.78	1.72	5.8	12.1	15
Frieberger 40120/99	(100)		0.8	0.23 0.5 0.66 0.73	1.45	3.55	31.5	29
AXT 20227/58	(100)	4500	6.8	0.28 0.55 0.64 0.73	1.61	5.12	8.9	19
Outokumpu 2331/123	(100)	5000	0.3	0.40 0.42 0.68 0.76	1.51 (Hersteller)	1.76	36.4	38
Wacker 20819/82	(100)	5600	4.5	0.39 0.67 0.73 0.74		3.4	38	35

Table 1: Characterization of GaAs-wafer

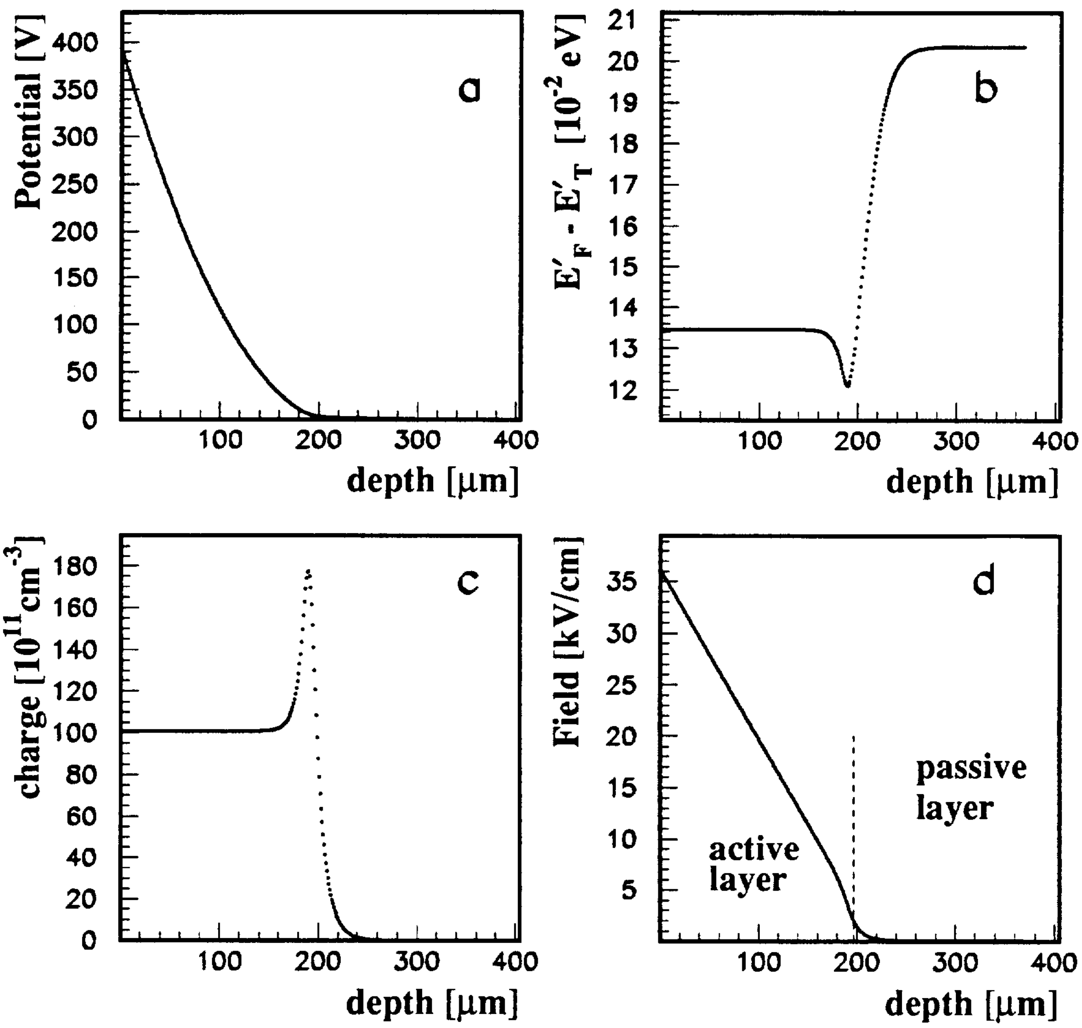


Figure 2: Monte Carlo simulation of E-field across the thickness of a GaAs Schottky detector

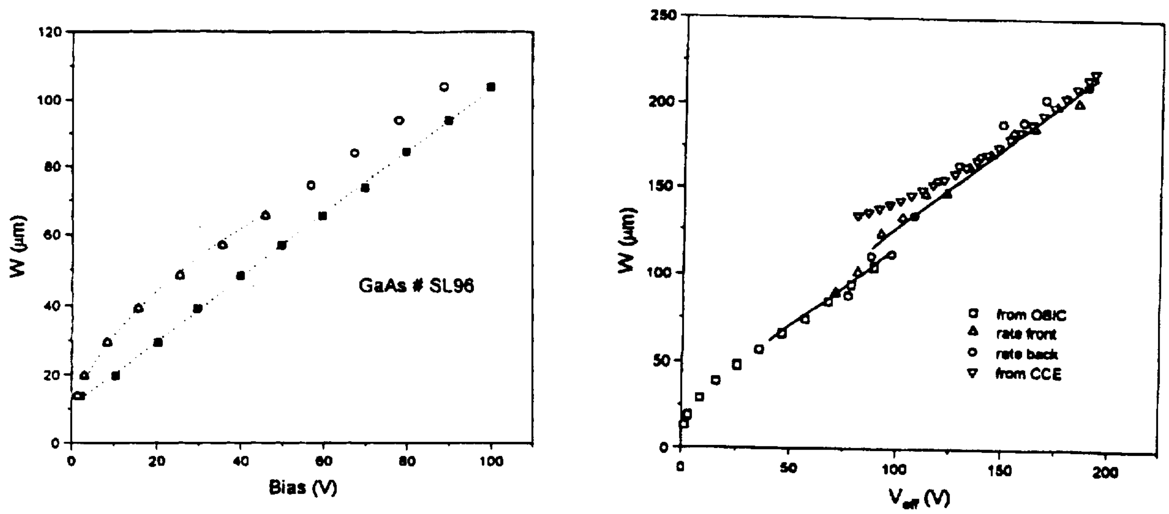


Figure 3: Variation with reverse bias V of the sensitive thickness W of a GaAs Schottky detector

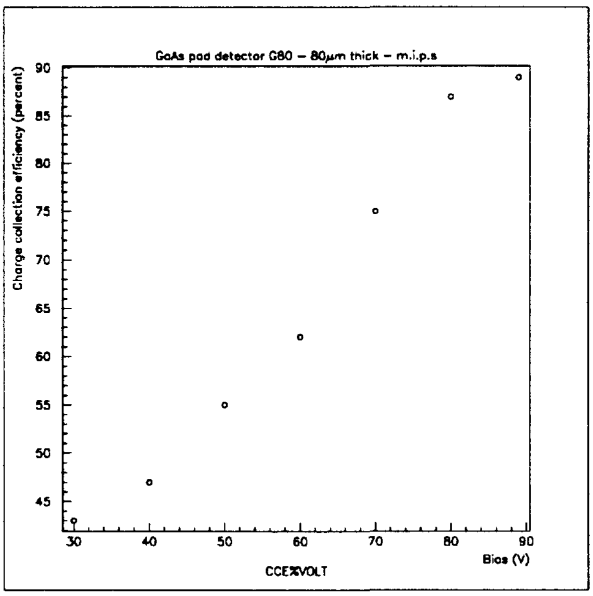
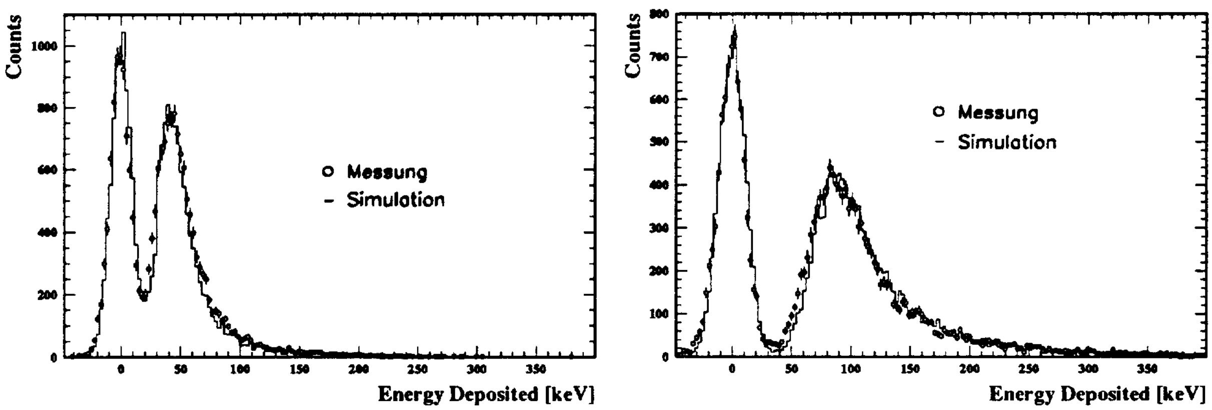


Figure 4: Variation with reverse bias V of the charge collection efficiency of a GaAs Schottky detector



(a) 200V (b) 400V

Figure 5: Comparison of Monte Carlo simulation of response to minimum ionising particles (m.i.p.s) and measured pulse height spectra at two bias voltages in a $350 \mu m$ thick Schottky diode detector

and hole traps in the semi-insulating GaAs [11, 19] have been inconclusive so far. Figure 6 shows the measured correlation between trap energies, concentrations and charge collection efficiency for simple pad detectors subjected to different annealing treatments so as to vary the trap concentrations. No direct link is seen with any single trap in measurements by the Bologna group in collaboration with physicists from MASPEC. Similar studies of the effects of annealing variations have been made at UMIST [20] and ANSTO [21]. Semi-insulating material from various different suppliers is also being compared in other laboratories in the RD8 collaboration. So far, no obvious pattern has been unambiguously established. Systematic studies by the Freiburg group [15] on wafer material from six different suppliers, however, show indications of correlations between charge collection efficiency and the concentration of "active" EL2 traps or leakage current density as measured by a range of techniques, (cf. Fig.6). The same Figure shows evidence of a similar correlation with the dielectric relaxation time of the material [2].

3.3 Epitaxial GaAs

High purity Liquid Phase Epitaxial (LPE) GaAs has been shown to provide 100% charge collection efficiency and to have properties similar to silicon in terms of depletion depth variation with reverse bias. The donor concentration has to be less than $10^{14}/cm^3$ for satisfactory operation, however, and this is difficult to achieve in large areas and/or thicknesses in excess of 100 microns. Successful samples have been prepared at ANSTO [22], using both semiconducting and semi-insulating substrates, and in Stuttgart [23].

Neutron irradiation studies of LPE GaAs samples subjected to fluences up to $7 \times 10^{13} n/cm^2$ have been carried out at ANSTO [24]. Devices were characterised using DLTS, ODLTCS, I-V and C-V methods, and through measurements of the 59.4 keV ^{241}Am gamma-ray line. While silicon control samples could no longer resolve the gamma-ray line after $\sim 10^{13} n/cm^2$, the GaAs detectors were still able to do so and their C-V characteristic adhered to normal Schottky barrier depletion theory up to the maximum fluence. The potential use of LPE material in LHC applications such as vertex detector pixel layers will ultimately depend on verification of the radiation resistance over a larger dose range and certainly on cost.

Successful production of LPE GaAs of suitable thickness and quality would also create many new opportunities for applications outside H.E.P. For example, a collaboration agreement has recently been established between RD8 groups in ANSTO and Sheffield and X-ray astronomers in Leicester to develop

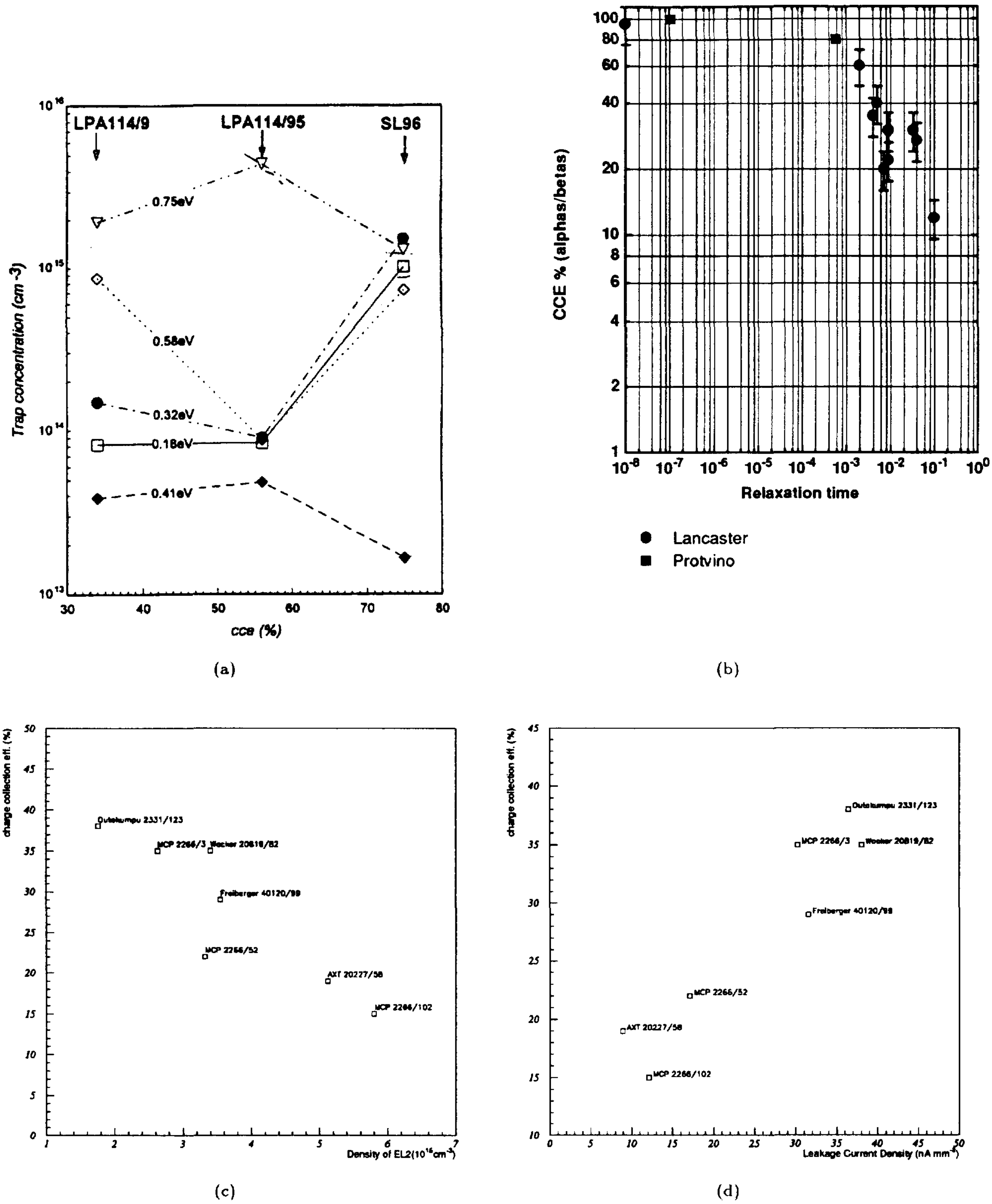


Figure 6: Correlation of charge collection efficiency with (a) trap concentrations,(d) material dielectric relaxation time, (c) "active" EL2 concentration and (d) leakage current density

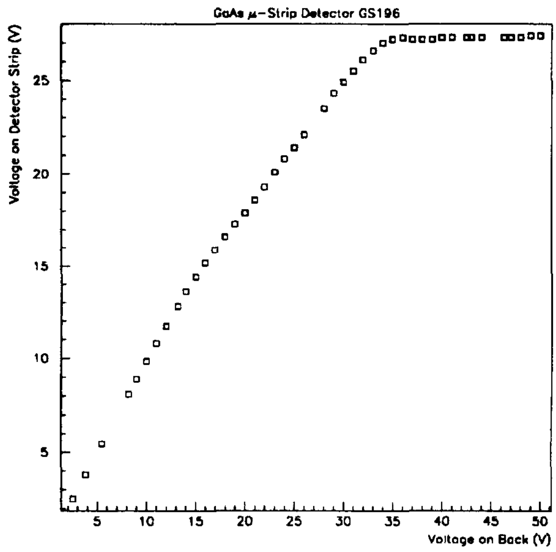


Figure 7: Bias strip operation of GaAs microstrip detectors

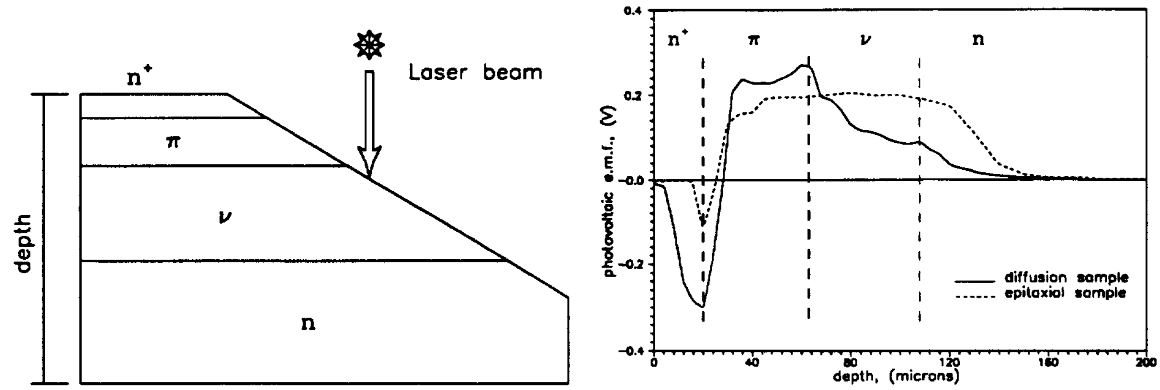
GaAs detectors, (pixel or CCD), for applications in X-ray astronomy. Medical imaging applications of GaAs pixel detectors are also under investigation with medical physics groups in Pisa and Ferrara.

4 Test Beam Studies

4.1 Microstrip Detector Results

The first microstrip detectors tested within the RD8 collaboration showed a wide range of signal/noise and charge collection efficiency (c.c.e.) values (cf. [1]). The first commercially-fabricated microstrip detectors from GEC-Marconi, for example, provided c.c.e. values of around 50% from 200 micron thick detectors. It has become increasingly clear that the range of observed c.c.e. values is related to the nature of the non-uniform electric field distribution through the detector thickness and to the consequently inefficient collection of charge from a fraction of that thickness, as described below. Improved understanding of this effect gives us more confidence in predicting improved properties in future detectors.
First results have also been obtained with double-sided detectors, using discrete decoupling capacitors [25]. An apparent signal charge inequality from the two sides appears to be due to charge spreading in the relatively "dead", low-field region close to the ohmic contact. Operation of similar, thinner detectors closer to the region of full depletion should remove this limitation. Collaboration members are also actively investigating alternative processing technologies for preparation of the back contact metallisation which would extend the maximum applicable reverse bias and facilitate fully-depleted operation.

Progress has also been made in reach-through biasing methods for GaAs microstrip detectors [26], as illustrated in Figure 7. Optimisation of the biasing geometry will continue with the production of commercial prototype detectors incorporating a range of test structures.
The Protvino group has recently tested the first microstrip detectors fabricated using the technology, developed in Tomsk, of in-diffusion of deep-level donors of Fe or Cr into the semi-insulating wafer [27]. The resultant material profile is illustrated in Figure 8 with examples of the performance of simple pad



(a) Profiling method

(b) Charge carrier concentration

Figure 8: Profile of Russian microstrip detectors fabricated in Tomsk

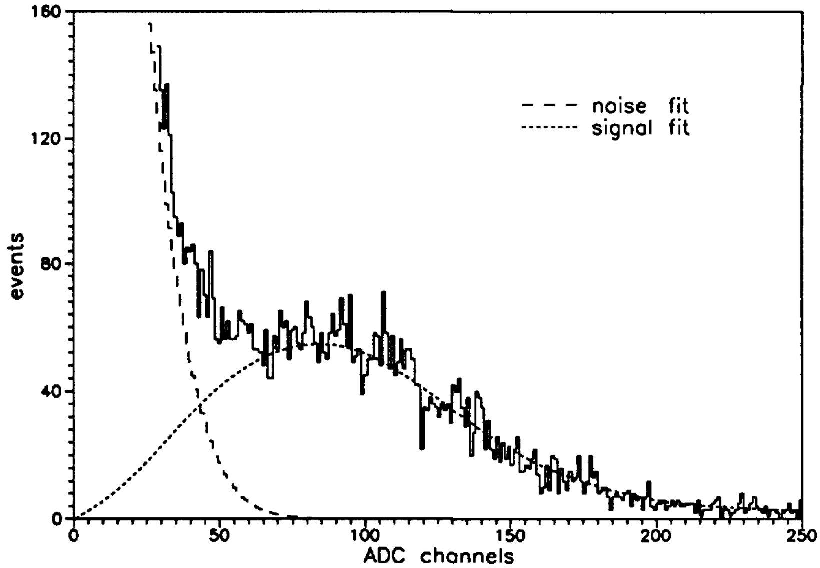
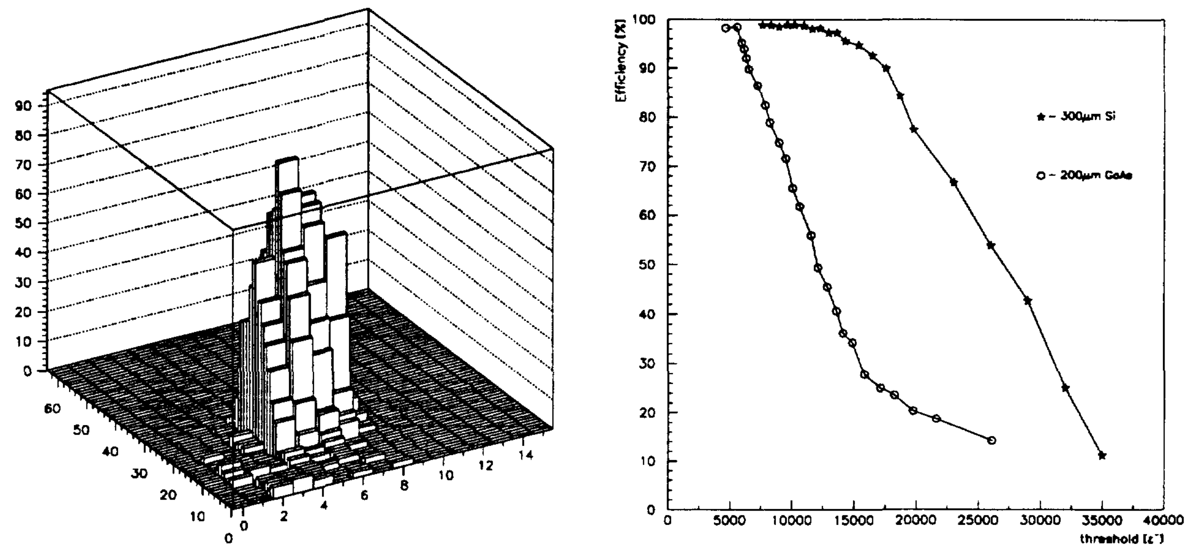


Figure 9: First test beam results from Russian microstrip detectors

detectors of this type. Recent test beam evaluation of the first microstrip detectors of this type is shown in Figure 9. With the inter-strip gap as shown, a relatively 'dead' zone is apparent between the metallic strip electrodes. Further studies of the dependence of this effect on strip aspect ratio are now under way, as are evaluations of the radiation hardness of microstrip detectors of this type. The first prototype GaAs pixel detectors were fabricated in Glasgow early this year, with mask designs used by the CERN Microelectronics group for their silicon pixel devices. The detectors were bump-bonded to the Omega2, digital read-out chip by GEC-Marconi, Caswell, and tested in a CERN test beam together with two silicon pixel detectors of identical geometry [28]. The beam profile detected from coincident hits in the



(a) Beam profile

(b) Discriminator threshold scan

Figure 10: Results of tests of first pixel detector in GaAs

three detectors is shown in Figure 10. The relative efficiency of the GaAs pixel layer as a function of the read-out discriminator threshold is also shown in this Figure. The results of this test are very encouraging, particularly since further test beam work has explained the apparent deficiency of collected charge from the GaAs, which was inconsistent with laboratory measurements of the signal charge from m.i.p.'s. The latest results, showing that the GaAs pixel detectors tested were competitive in efficiency with the silicon devices in the same test, are also illustrated in Figure 10.

4.2 Test Beam running in 1994

Our aims in test beam running this year are firstly to investigate commercially produced microstrip detectors and secondly to continue studies of microstrip detectors fabricated in our own laboratories, in particular with respect to optimum strip pitch and aspect ratio, position and energy resolution and wafer and processing variations in detector fabrication.

The first commercially-made LHC prototype, 50 micron pitch microstrip detectors, $53 \times 23mm^2$ in area and 200 microns thick, together with test structures of various aspect ratios, were received from Alenia SpA on August 1st, 1994. Preliminary analysis of data collected with one of these detectors is still in progress, but the results obtained so far are promising, with spatial accuracy of $\approx 14\mu m$ already obtainable from fits to tracks through the GaAs detector under test and the four layers of the Strasbourg group's silicon microstrip telescope [29]. Fig.11 shows the distribution of residuals in track fits to 70 GeV pion hits in the four silicon layers of the Strasbourg telescope and the A.C.-coupled Alenia prototype microstrip detector, (50 microns pitch, 200 microns thick, 180V bias). A full analysis of these data is still in progress. The GaAs microstrip detectors will continue to be tested in particle beams during the next two months. In addition, a set of commercial prototype microstrip detectors has recently been produced

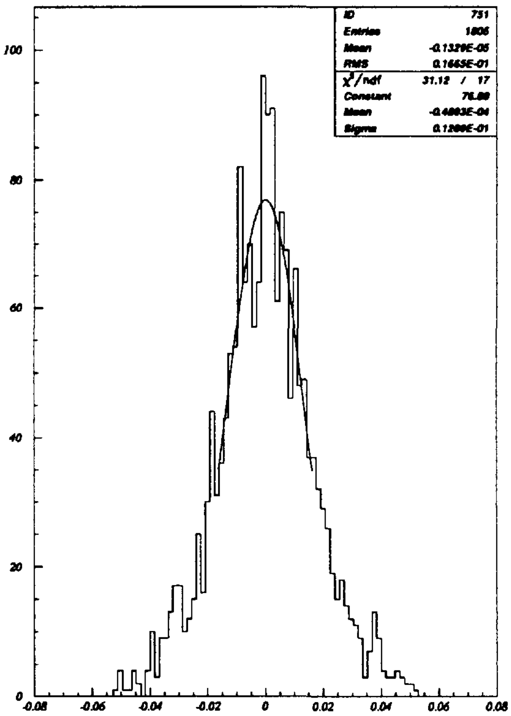


Figure 11: Distribution of residuals in track fit to four silicon and one (Alenia) GaAs track hits in test beam

	sensor 1	sensor 2
Thickness	500μ	250μ
Pitch	200μ	200μ
Strip width	100μ	100μ
Strip length	$22mm$	$22mm$
#of strips	78 (total)	78 (total)
#of strips	59 (readout)	59 (readout)
sensitive area : $\sim 20 \times 12mm^2$		

Table 2: Parameters of Aachen Microstrip Detectors

by E.E.V. in the U.K. - these will be extensively studied in the laboratory before evaluation in a test beam, hopefully early next year.

The Freiburg group has also tested microstrip detectors fabricated "in-house" in collaboration with the Fraunhofer Institute in Freiburg. Systematic studies have been made of the response variation across the gap between adjacent strips with alpha particle sources and a range of strip pitches (cf. Fig.12 and Fig.13 show the microstrip geometries and the charge fraction detected in adjacent strips for the various strip pitches studied. Test beam evaluation of Freiburg microstrip detectors of $44\mu m$ pitch read out with VIKING preamplifiers, using 5 GeV pions in the T10 beam at the CERN CPS, has produced the encouraging results shown in Fig.14.

For beam tests at CERN during August 1994, the Aachen group have also built several GaAs microstrip detectors. Two of these are fixed on a ceramic and a G10 board, respectively, enclosed in an aluminium box and mounted on a movable platform in the X3 beam. The detector characteristics are summarized in Table2 : The detector strips are capacitively coupled to low noise VIKING preamplifier chips [30] followed by dedicated multiplexed read out electronics and DAQ. Fig.15 shows the measured cluster pulse height from 50 GeV pions incident on sensor 1, with a bias of 300V. The signal variation with bias and angle of incidence of the beam particles is shown in Fig.16. The distribution of residuals in fitted tracks, shown in Fig.17, has an r.m.s. value compatible with (strip pitch/$\sqrt{12}$).

5 Radiation Hardness Studies

5.1 Irradiation Studies

In order to study the radiation hardness of GaAs detectors, 75 detectors made in Aachen from SI-GaAs (VGF) with $3mm$ diameter (NiCr/Au) contacts were irradiated at the ISIS facility at RAL [31]. Some of the detectors were biased during irradiation (to 200 V). As expected, the behaviour of biased and unbiased detectors were found to be identical as there are no oxides or insulators that are capable of trapping charges. Fig.18 shows characteristic I-V curves of several detectors before and after n-irradiation with a dose of 10^{15} n/cm^2. The increase of reverse current is rather small, corresponding to a "damage constant", α_n of $\approx 10^{-19} A/cm$. The signal (in units of 10^3 electrons) for ^{90}Sr electrons (mips) is presented in Fig.19 as a function of the neutron flux for different bias voltages. Even at the highest radiation level all detectors work properly, the obtainable mip-signal being $\sim$ 8000 electrons. Fig.19 also displays the noise behaviour before and after irradiation for a shaping time of $1\mu s$, showing an increase of 10% - 15% at the highest doses. Simple Schottky pad detectors from Freiburg and Glasgow have also received neutron doses at the level of $10^{14} n/cm^2$ and above in ISIS. Similar results have been obtained with *p-i-n* detectors made by the Sheffield group. Results of these irradiations, illustrated in Fig.20, are comparable with the Aachen results but require confirmation at the highest doses through irradiation of larger statistical samples. This is planned for October, 1994.

The most promising results so far on neutron radiation resistance in GaAs have been obtained by the Russian group from Protvino, testing detectors made in Tomsk by in-diffusion of deep-level dopants such

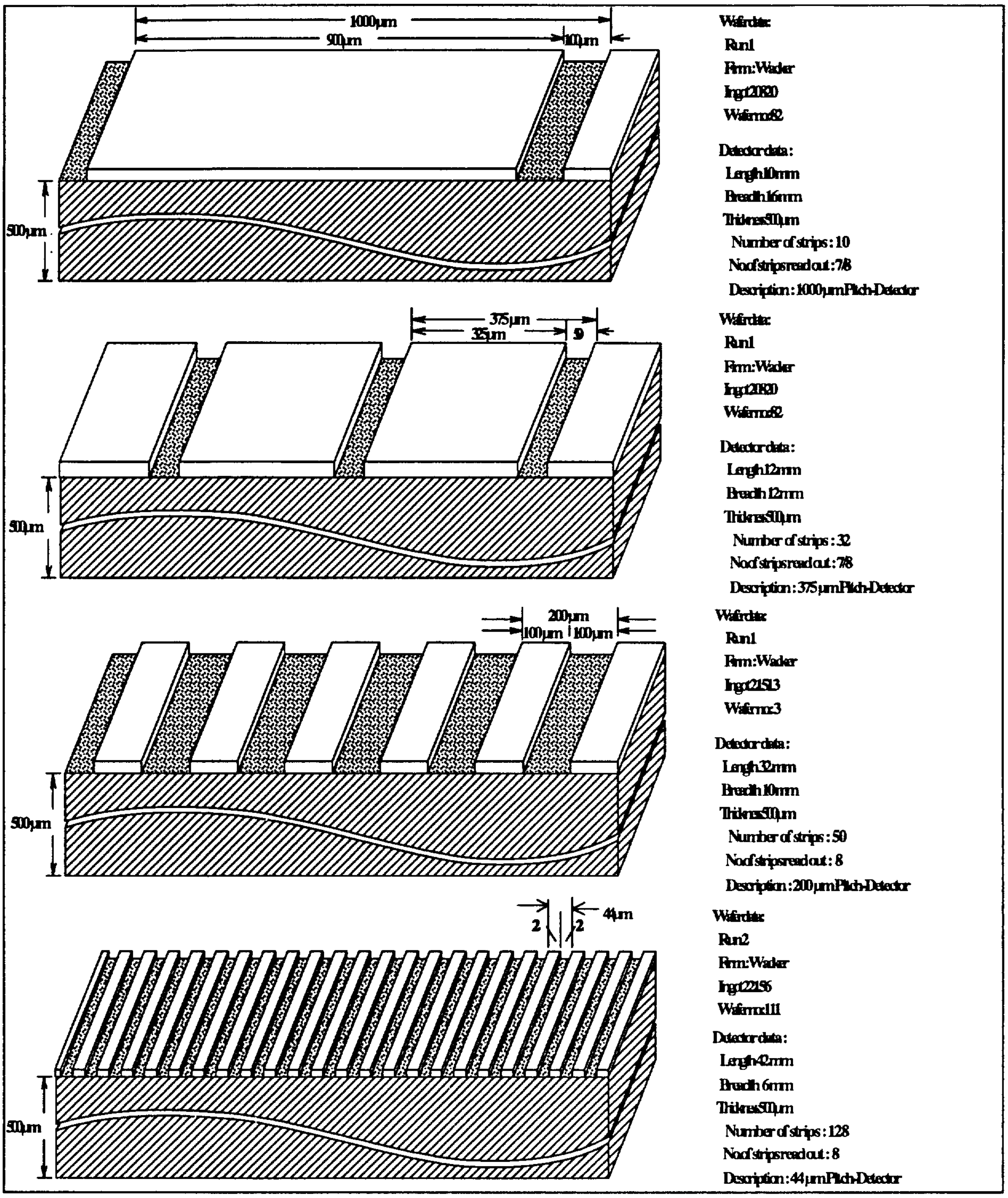


Figure 12: Geometry of tested microstrip detectors

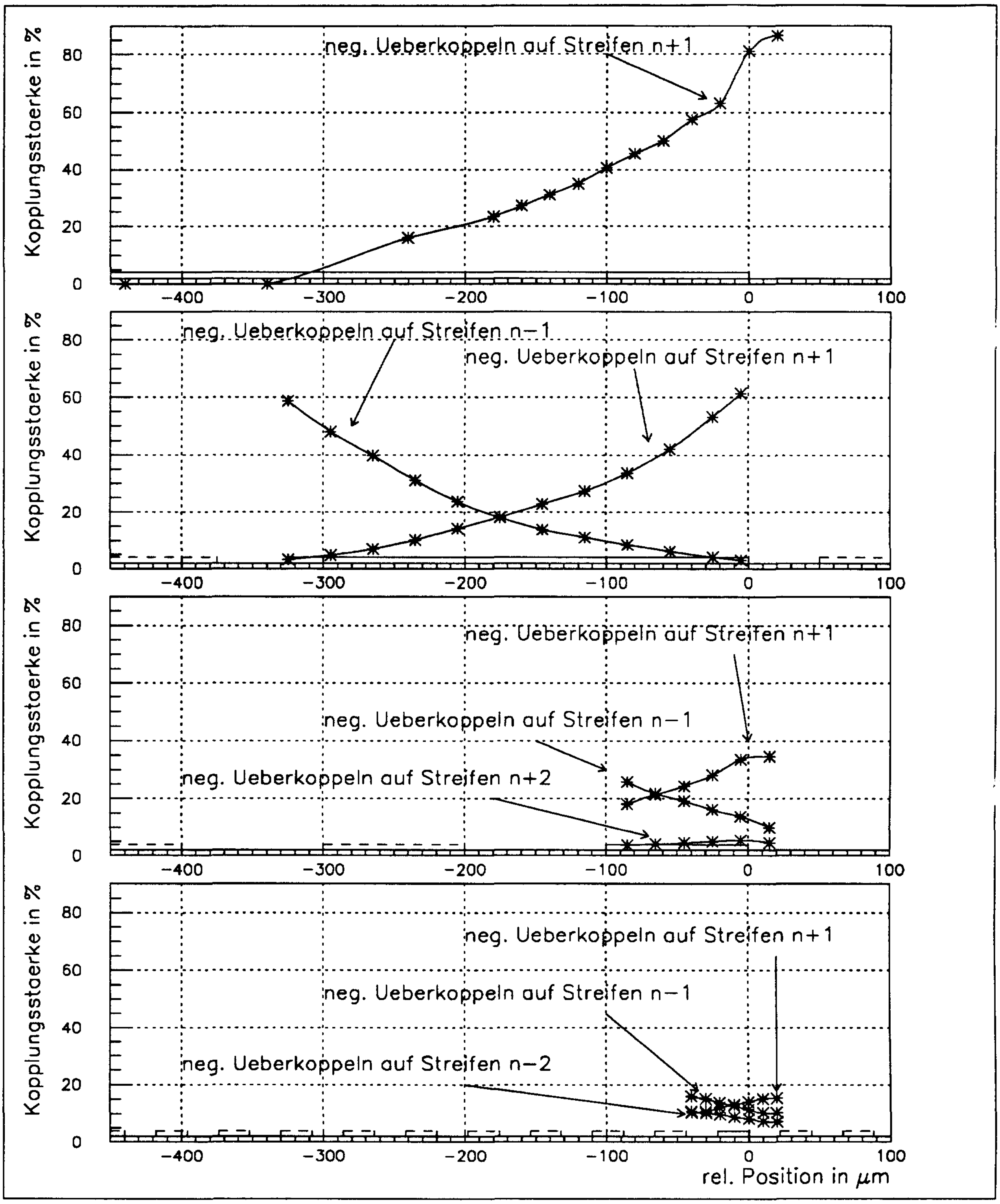


Figure 13: Extent of charge sharing between adjacent strips

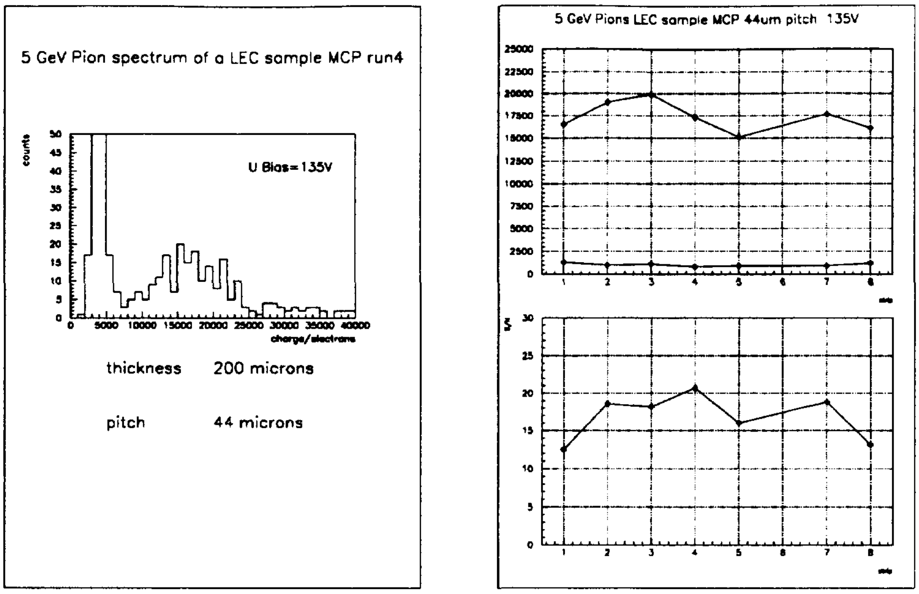


Figure 14: Response to 5 GeV pions of a Freiburg microstrip detector; (a) Pulse height from m.i.p.s and (b) uniformity across the strips in signal, noise and S/N ratio

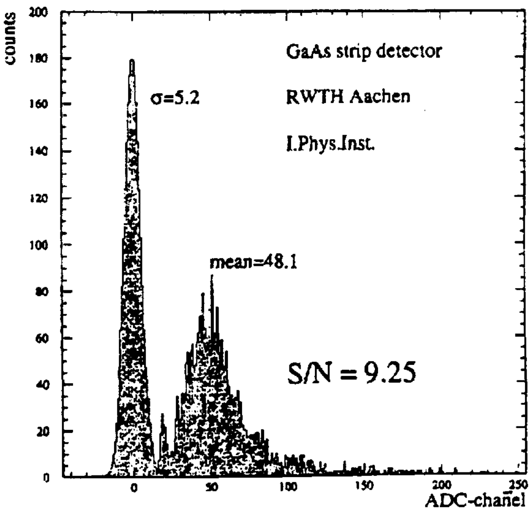


Figure 15: Cluster pulse height and strip multiplicity from 50 GeV pions in 500 micron thick GaAs microstrip detector with 300V bias

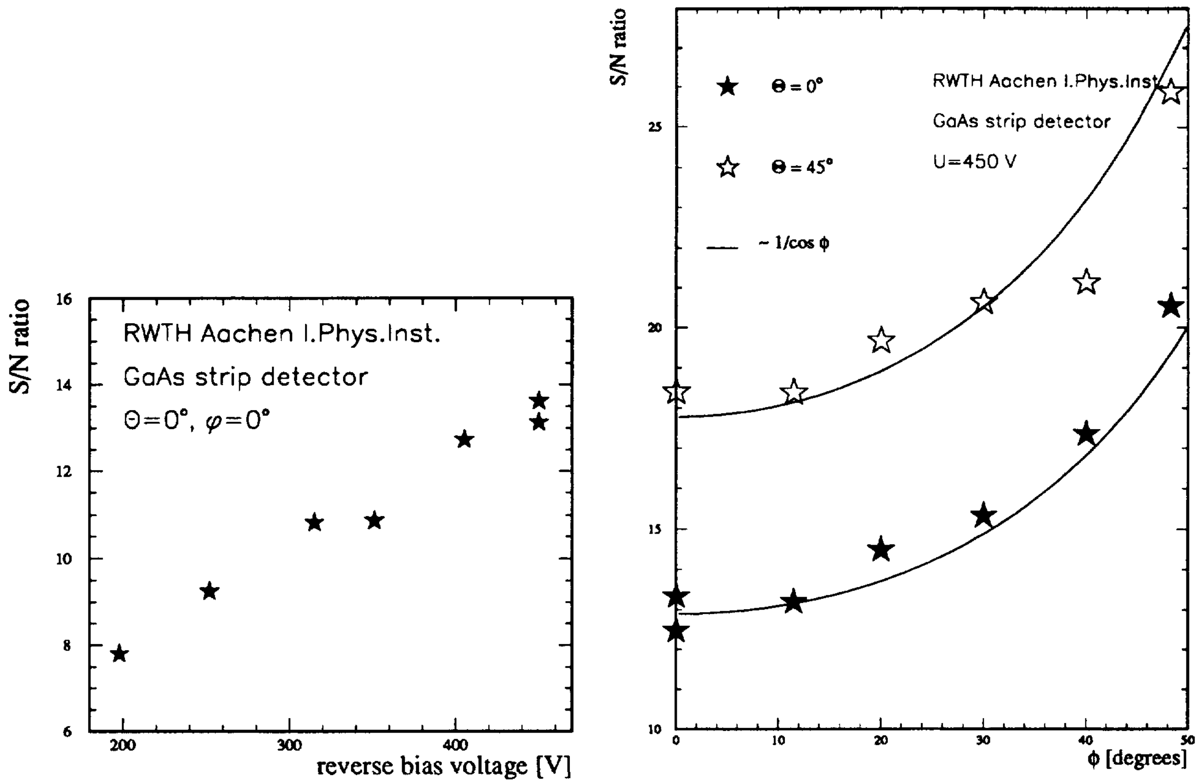


Figure 16: Signal variation with (a) bias and (b) angle of incidence for an Aachen microstrip detector

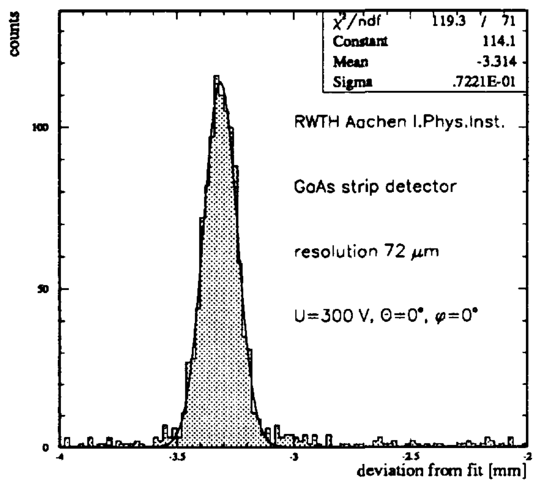


Figure 17: Distribution of residuals for fitted tracks

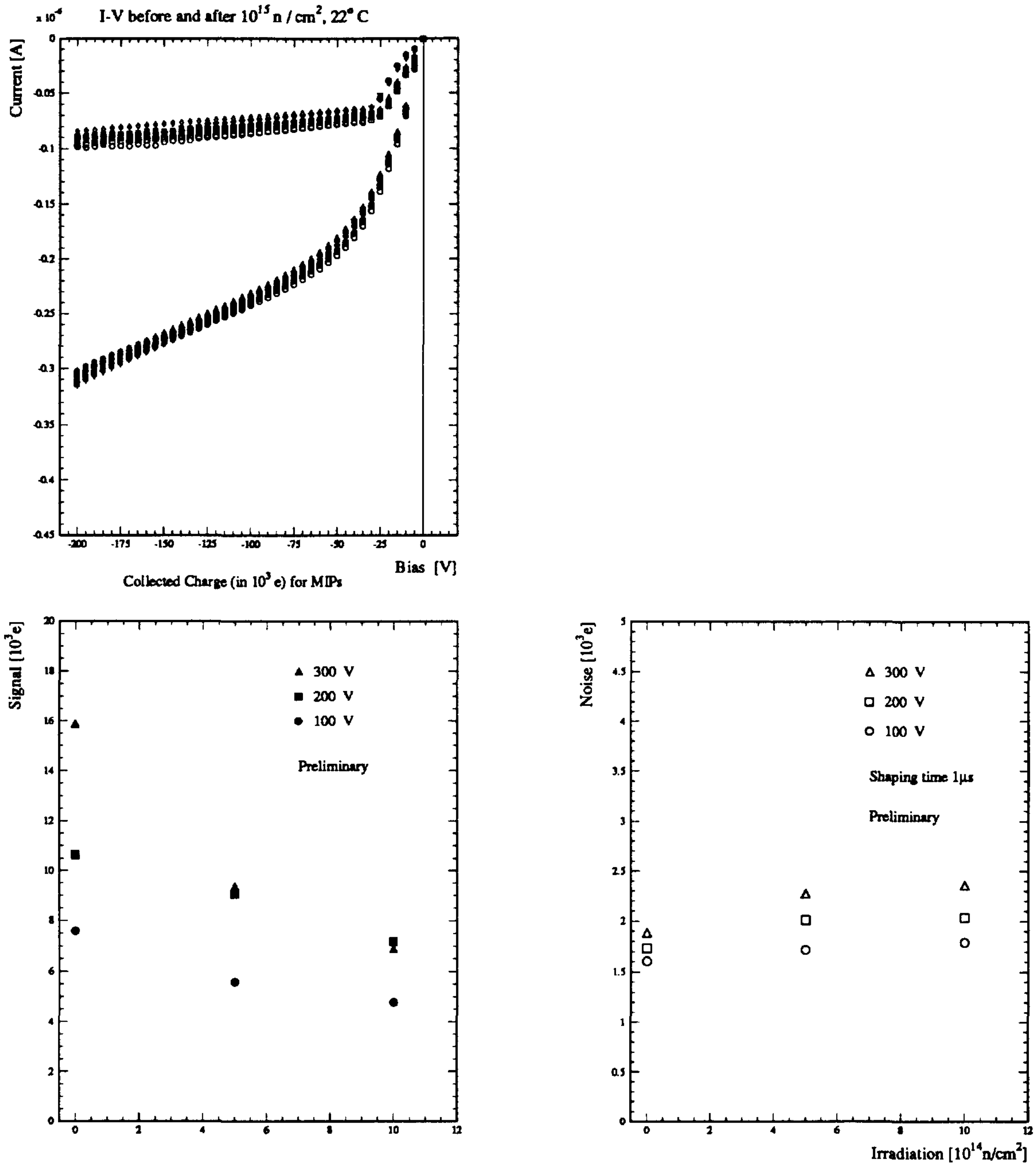


Figure 18: Collected signal charge and noise signal from simple, 3mm diameter electrode GaAs detectors versus neutron dose

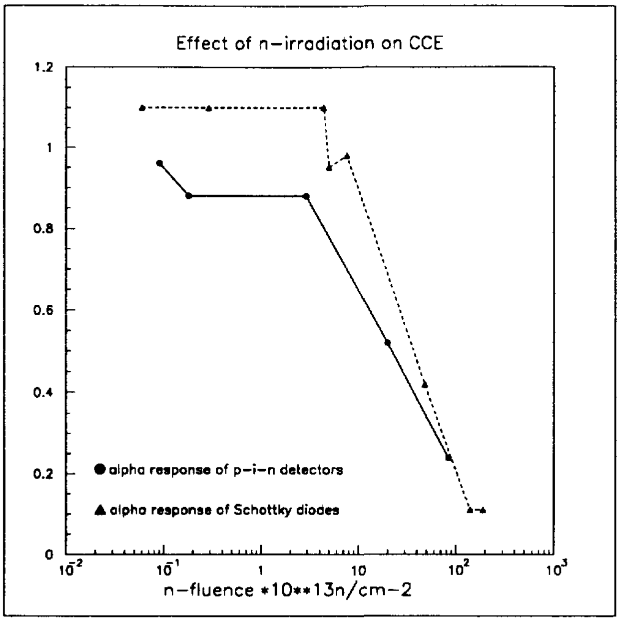


Figure 19: Variation of response of simple pad detectors with neutron dose

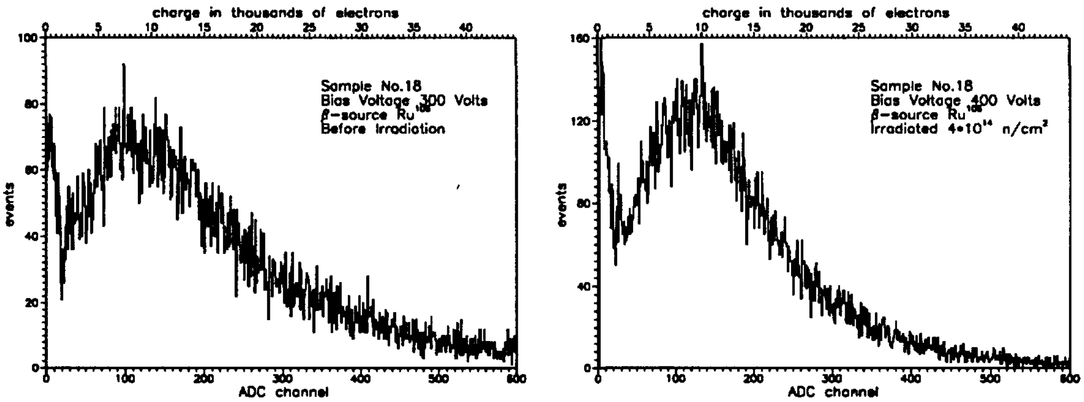


Figure 20: Pulse height distribution from beta m.i.p.s in a Tomsk detector before and after neutron irradiation

as Fe or Cr into semi-insulating substrate material [27]. The variation in depth of the charge carrier concentration was investigated as shown in Fig.8. The pulse height distribution from minimum ionising beta particles from a ^{106}Ru source is shown in Fig.20 - a similar spectrum was subsequently obtained in tests at CERN with an LHC prototype front-end chip [32]. The variation in response with neutron fluence of the Tomsk detectors is illustrated in Fig.21.

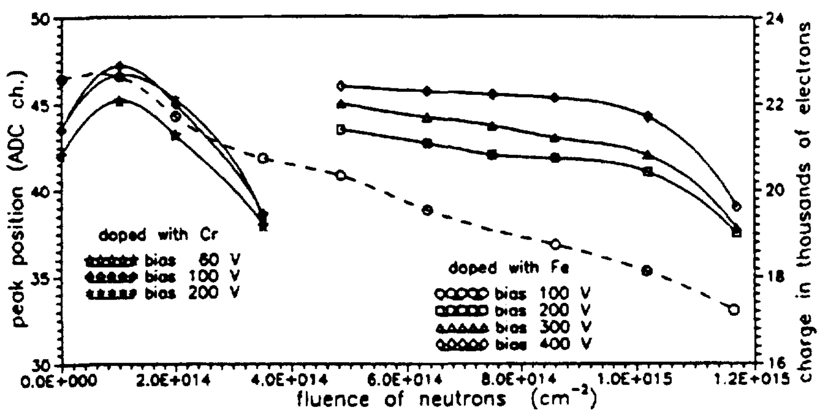


Figure 21: Variation of collected signal charge with neutron dose for Tomsk detectors

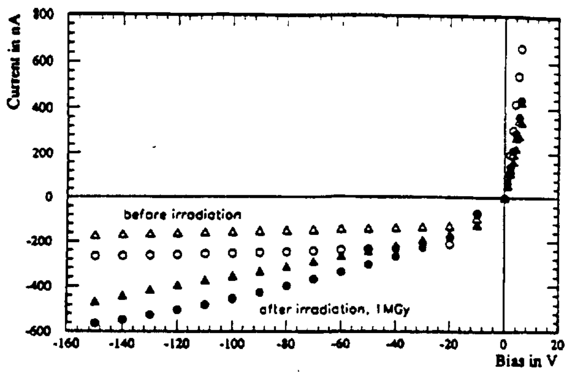


Figure 22: Effects of irradiation of pad detectors with 1 MGy of gamma-rays and 3MeV electrons

5.2 Gamma-ray, electron and pion irradiation

Gamma-ray and (3 MeV) electron irradiation of simple pad detectors has been carried out by the Aachen and Freiburg groups at levels up to 1 MGy (100 MRad), as illustrated in Fig.22. The detectors are able to withstand this level of dose with only minor deterioration in performance.

In addition to evaluation of neutron hardness, two Glasgow pad detectors were exposed to a pion beam fluence of $\approx 10^{14}/cm^2$ at the P.S.I. accelerator during June, 1994. Analysis of these specimens is still in progress. Further irradiation of a larger statistical sample of detectors is also planned for the near future.

6 Electronics Studies

6.1 Detector test with LHC front-end chip

A simple pad detector from Tomsk has been tested at CERN using the BIPOLTEST read-out chip of the RD2 collaboration [32]. With this LHC-type read-out, the measured signal at both ambient temperature

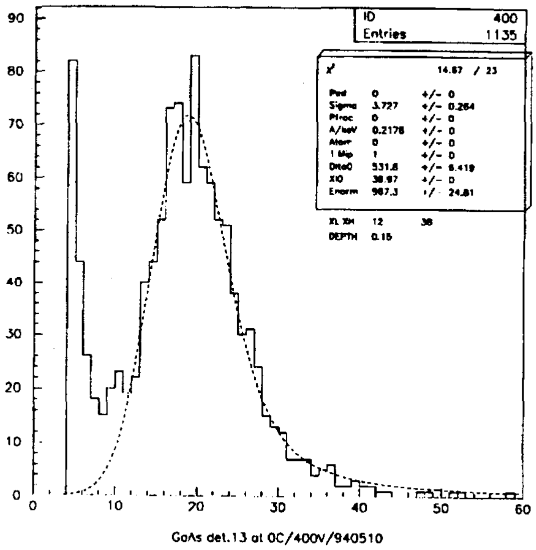


Figure 23: Pulse height due to minimum ionising beta particles measured with an ICON preamplifier on a Tomsk pad detector

and at 0^oC was above 20000 electrons, and in good agreement with the 95% charge collection efficiency measured by the Protvino group [33] on detectors of this type. The measured pulse height spectrum due to m.i.p.'s is shown in Fig.23.

6.2 Noise studies

Measurements have been made of the noise spectral density of typical GaAs pad detectors and candidate front-end preamplifier chips at the Politecnico di Milano [34, 10]. Fig.24 shows some recent results from such measurements. Similar measurements will be made on irradiated detectors in an attempt to correlate the signal degradation with the change in noise characteristics. The aim of this work is to optimise the front-end preamplifier to the specific GaAs noise characteristics.

6.3 Performance of GaAs HEMT's and HEMT-based Preamplifiers After Neutron Irradiation

Both the Aachen and Freiburg groups have undertaken studies of GaAs preamplifier possibilities. For example, investigations have been carried out by the Aachen group of the DC-,AC- and noise behaviour of GaAs-based operational amplifiers in C-HFET technology of 1μm gate length and 110μm and $330/mum$ gate width [35]. The gate currents were found to be of the order of 10 nA and the power consumption was typically 10 mW. A risetime of 4 ns was typical for all the devices.

For a total input capacitance of 5 pF and a shaping time of 25 ns the total ENC of an input transistor with a 330μm gate width was measured to be 760 electrons. As a function of the gate width the ENC had a shallow minimum of 550 electrons at 1400μm. However, this small improvement can be obtained only at the expense of increased power consumption and greater sensitivity to the shaping time. Thus the gate width of 330μm appears to be close to an overall optimum.

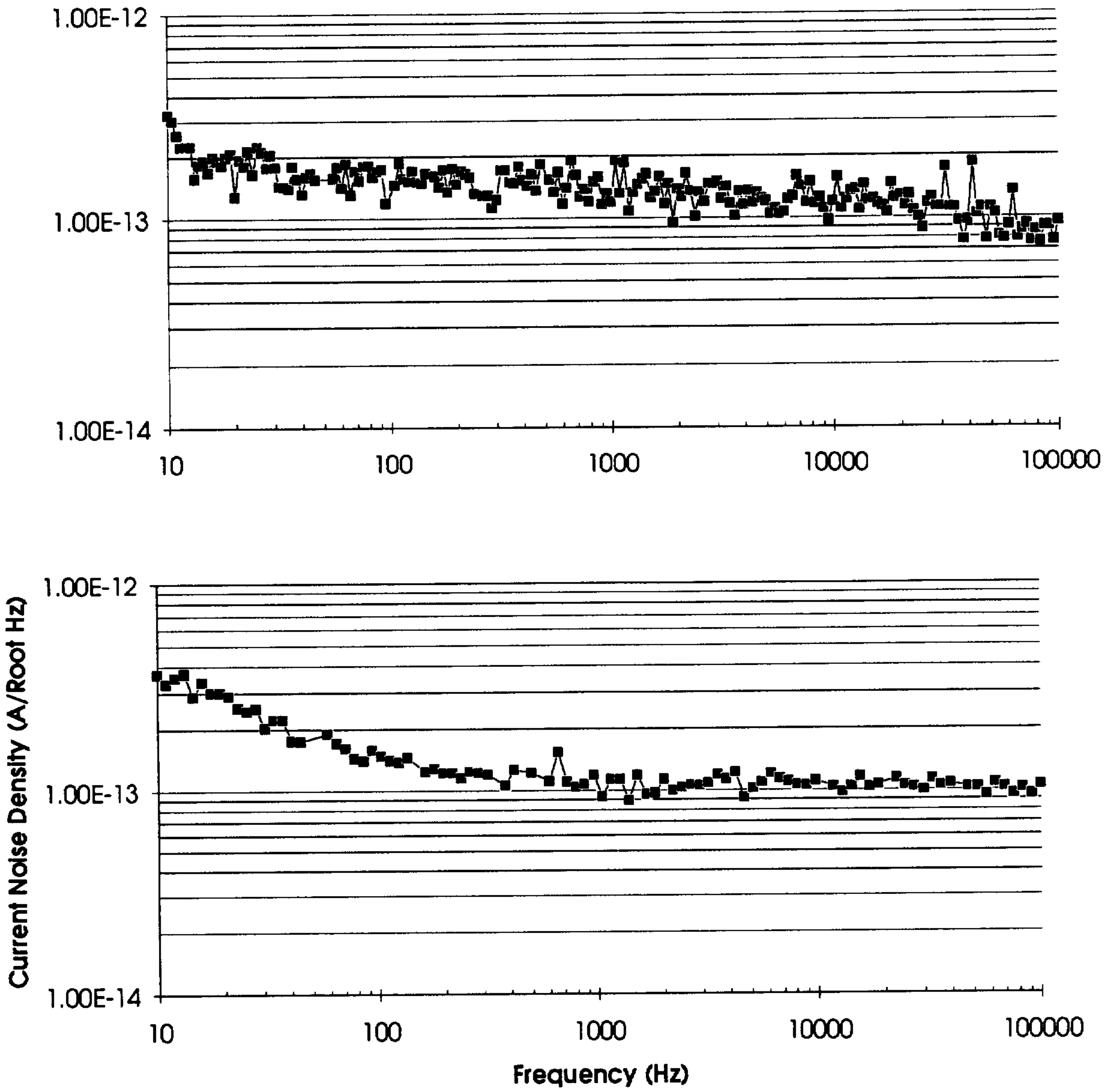


Figure 24: Current noise spectrum obtained for the 2mm and 3mm diameter pad detectors with a leakage current of 73.0nA.

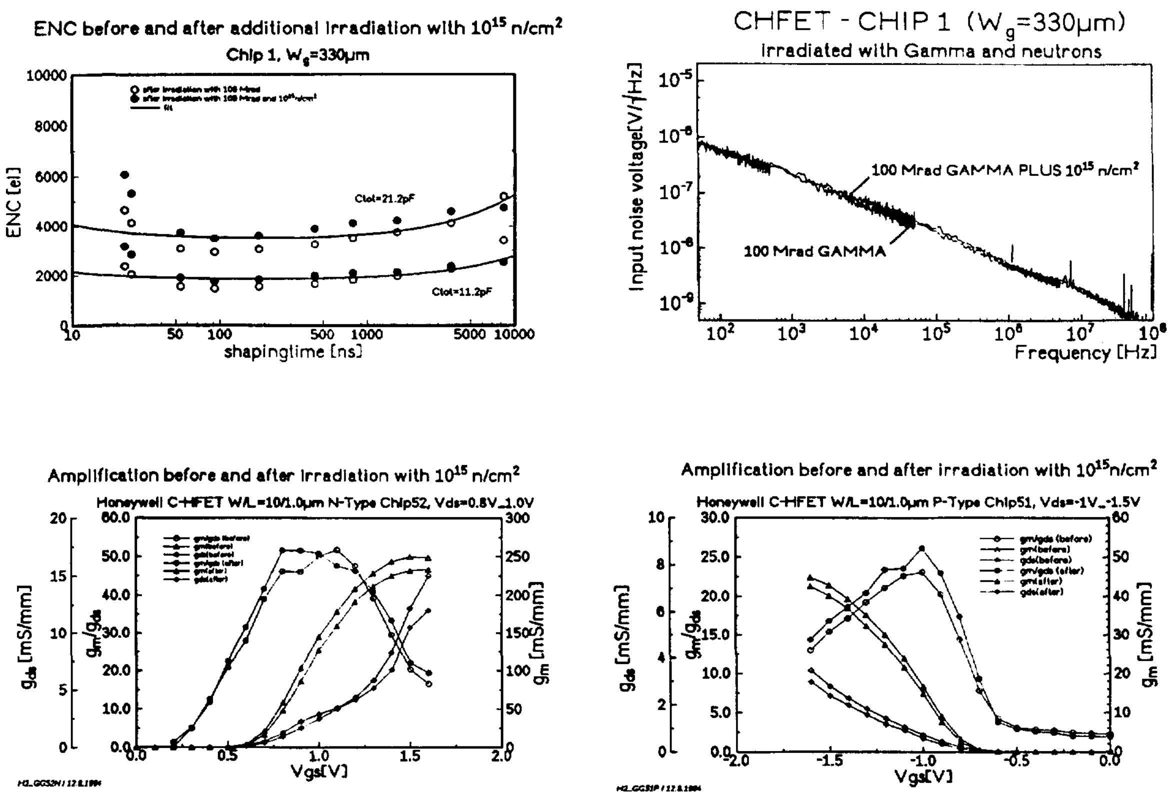


Figure 25: Effects of neutron irradiation on GaAs HEMT performance

The amplifiers were irradiated with 100 Mrad photons (^{60}Co) and with 10^{14} n/cm^2. As a result of the irradiation, changes in the AC-,and DC- and noise characteristics were found to be of the order of 10%.

The devices worked well in a liquid nitrogen atmosphere at 77K. A slight improvement in AC- and DC characteristics was observed and the noise was found to be reduced by a factor of two.

These amplifiers as well as a sample of single HEMT's were irradiated with an additional 10^{15} n/cm^2. Fig.25 shows noise measurements for a preamplifier with a gate width of 330μm using a spectrum analyzer and a special shaper system with a variable shaping time from 10 ns up to 10 μs , respectively. From these measurements an increase of ~30% of the 1/f-noise has been extracted. The DC-characteristics changed by $\leq$ 10%. The single HEMT's showed $\leq$ 10% decrease in amplification and no significant changes w.r.t. gate currents. Fig.25 shows the transimpedance (g_m), the output conductance (g_{ds}) and the amplification (g_m/g_{ds}) as a function of V_{gs} before and after irradiation for an N-type and a P-type transistor, respectively.

6.4 Optoelectronic Modulator development

In collaboration with the Department of Electrical and Electronic Engineering of Glasgow University, Multi-Quantum-Well modulators have been designed, fabricated and tested with a view to maximising the sensitivity of the modulator to the small signals from GaAs particle detectors [36]. The most promising structure tested to date is illustrated in Fig.26. The reflectance of the cavity illustrates the wavelength sensitivity. Modulation of an externally supplied laser beam (from a Ti-sapphire laser pumped by a YAG laser) due to the variation of absorption with applied voltage across the modulator is also shown. The modulator/photodetector combination is found to be sensitive to signals from the detector as small as 10 mV.

6.5 Avalanche Detectors

The Aachen group have started a close collaboration with a group at the research centre at Jülich, Germany, who are experienced in building and processing GaAs detectors. Recently this group has managed to realize an AlGaAs/GaAs avalanche photodiode with separate absorption- and multiplication regions (SAM-APD) as an X-ray detector. Gains higher than 20 could be achieved with a staircaselike multiplication region. Typical dark currents of 100pA at 90% of the breakdown voltage were measured with an active area of $320 \times 450\mu m^2$ [37]. As an example, Fig.27 shows energy spectra obtained with an ^{241}Am source in two devices with different gains. Since this amplification does not introduce any additional noise, it could considerably improve the signal/noise ratio in our applications for the detection of minimum ionizing particles. First laboratory tests of avalanche detectors in Aachen are expected before the end of 1994.

7 Tracking Studies for LHC Applications

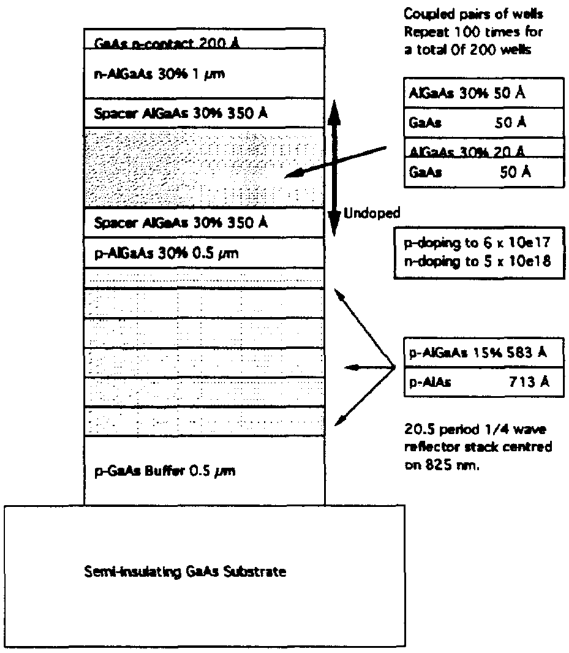
The main aims of our ongoing studies are:

- to attempt to understand neutron radiation damage mechanisms and how to ensure effective operation of GaAs microstrip detectors for neutron doses up to at least $5 \times 10^{14} n/cm^2$
- to determine the optimum microstrip pitch and aspect ratio for GaAs tracking elements
- to evaluate the extent of any "dead zone" between microstrip electrodes
- to determine the most effective biasing and decoupling arrangement for both single-sided and double-sided detectors

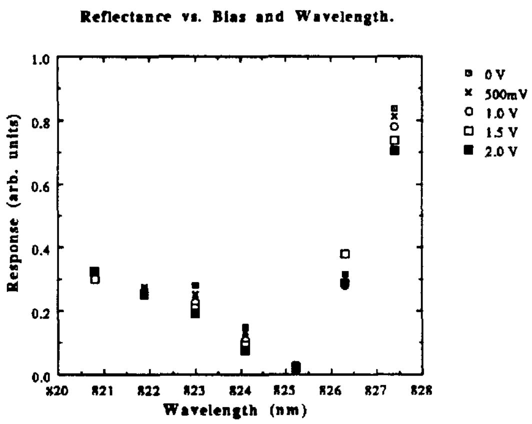
Further work will also be carried out on GaAs pixel detectors, both on semi-insulating and on LPE epitaxial GaAs layers. At present, it is proposed that these detectors be bump-bonded to Omega2 readout chips from the CERN group, but progress with alternative bonding technologies will be carefully monitored. The next step towards a realistic pixel detector will be the fabrication of a "ladder" of pixel elements, similar to the silicon detector ladders presently in use at the Omega spectrometer.

8 Requests to DRDC

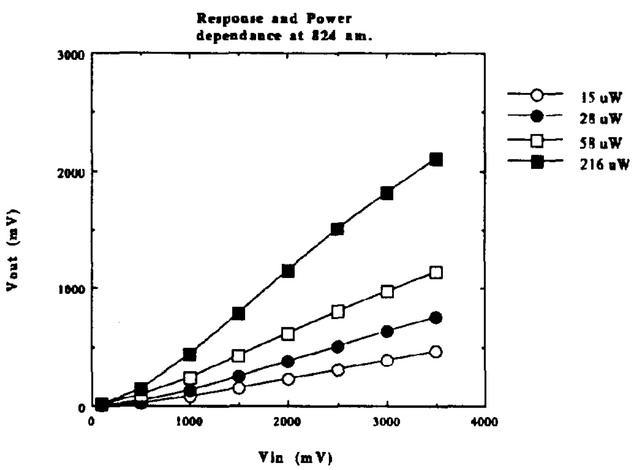
An essential aspect of the continuing development of GaAs detectors, both microstrip and pixel devices, is the trend towards commercial production of detectors which has begun in earnest this year. While we have initiated discussions with some manufacturers concerning the probable costs of large scale production of these detectors, these discussions require continuing effort and the technology requires further refinement to achieve the best value for money in the final ordering process. We therefore request additional support from the DRDC to enable us to place orders for at least one production run of microstrip detectors during this year, to allow continued development of commercial production of these detectors. Detailed tests of these detectors would entail test beam running, for which we request ten days of beam time. We bid in addition for consumables costs, (particularly for costs associated with wafer and mask purchase and processing in our own labs.), for costs of read-out hybrid circuits and front-end chips and for commercial bump-bonding of a further sample of 10 pixel detectors.



(a) structure



(b) reflectance



(c) response

Figure 26: Results of tests of first Multi-Quantum Well Modulator

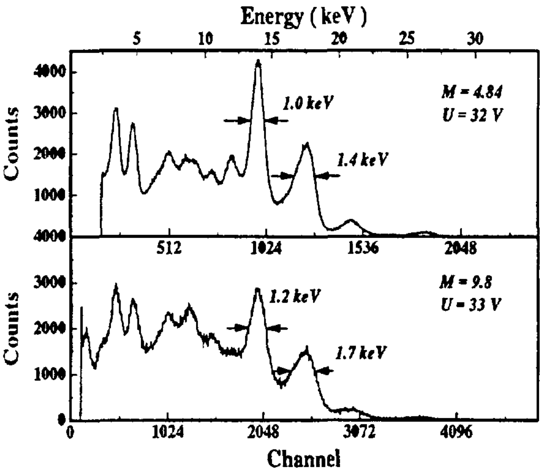


Figure 27: Gamma-ray spectra from ^{241}Am source measured with a GaAs avalanche diode detector

We bid also for a modest allocation of computing time on central CERN computers, to allow the partial analysis of our test beam data and to allow the refinement of Monte Carlo models of charge transportation in GaAs.

Summary of equipment requests		
Commercial Detectors		40kSfr
Prototype electronics	Hybrids	5kSfr
Consumables, (Wafers,Masks etc.)		20kSfr
Total		**65kSfr**
Computing time	VXCERN	20hrs
	CERNVM	20hrs
SPS test beam time		10 days

9 Conclusions

We have demonstrated that we can make GaAs microstrip and pad particle detectors routinely and reliably with few failures. The speed and the radiation hardness have been proven at LHC levels, with no need for detector cooling or adjustment of reverse bias voltage and with only modest increase in leakage current. For the 200 micron thickness we propose for LHC applications, GaAs microstrip detectors will work as well as 300 micron thick silicon detectors, with fewer operational complications. The material penalty to be paid is an additional $0.54\% X_0$ for each 200 micron thick GaAs layer relative to a 300 micron thick silicon layer. The read-out electronics can be identical in the two cases. Pixel detectors in GaAs have been demonstrated successfully for the first time and offer increasingly interesting scope for applications at the LHC and elsewhere.

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References

[1] RD8 status report, CERN/DRDC 93-22

[2] J.Santana, *"Lifetime" and "Relaxation" conditions of GaAs*
Universdity of Lancaster/RD8 internal note, July 1994

[3] S.T.Lai, B.D.Nener, L.Faraone, K.S.A.Butcher and D.Alexiev, *Characterisation of LEC Grown Semi-Insulating GaAs Treated with H_2 Plasma,*
Australian Compound Optoelectronics Materials and Devices Conference, ANU, Canberra, December 6-8, 1993;
S.T.Lai, B.D.Nener, D.Alexiev and K.S.A.Butcher,
Optical Deep-Level Transient Conductance Characterisation of Semi-Insulating Gallium Arsenide Treated with Hydrogen Plasma,
Jpn. J. Appl. Phys. **33** (1994) 199-201

[4] C.M.Buttar, *New results on GaAs detectors,*
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany;
A preliminary study of the response of GaAs detectors to alpha particles,
Proc. 2nd. London Conference on Position Sensitive Detectors, London, September 1990
Nucl.Instr.and Meth. in Phys.Res. **A310** (1991) 208

[5] S.D'Auria, Ph.D. Thesis, University of Bologna, 1993

[6] K.Berwick et al., *Imaging of high field regions in SI GaAs particle detectors,*
Conference on Defect Recognition and Image Processing in Semiconductors and Devices, Santander, 1993;
K.Berwick et al., Proc. MRS Spring Meeting, Symp. F, San Francisco, 1993

[7] A.Cavallini et al., *OBIC investigations of the electric field in GaAs detectors,*
submitted to Nucl.Instr. and Meth. in Phys. Res., 1994 and
M.Alietti et al., *An optical-beam-induced-current study of active region and charge collection efficiency of GaAs particle detectors,*
CERN preprint CERN/LAA/94-28

[8] K.Butcher et al., *Proton Microprobe Investigation of Semiconductor Detector Surface Effects,*
Submitted for publication to N.I.M.

[9] S.P.Beaumont et al., *New results on GaAs solid-state detectors for High Energy Physics,*
Proc. of 4th San Miniato Topical Seminar on Experimental Apparatus for High Energy Physics and Astrophysics,
June 1990 (World-Scientific 1991, P.Giusti, F.L.Navarria and P.G.Pelfer eds.)

[10] J.Ludwig, *GaAs Microstrip Detectors,*
Contribution to I.C.H.E.P. 94, Glasgow July 20-27th, 1994

[11] J.Santana et al., *gaAs DLTS and I-U Studies,*
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany. and Nucl.Instr. and Meth.in Phys.Res. **A342** (1994) 83

[12] S.T.Lai, D.Alexiev and B.D.Nener,
Characterisation of Defects Induced by Electron, Gamma and Neutron Irradiation on Semi-Insulating GaAs,
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany.

[13] R.Irsigler, *Rutherford Backscattering measurements*,
J.Chen, *Characterisation of GaAs Schottky contacts*,
D.Ebling, *Deep level characterisation by admittance spectroscopy*,
M.Fiederle, *Comparison of LEC GaAs wafers by Hall and PICTS measurements*,
T.Schmid, *Measurements with GaAs strip detectors*,
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany;
Invited talk by K.Runge at Celebration of 70th Birthday of H.Schopper, CERN, September 1994

[14] *Calculation of the Electric Field in GaAs Particle Detectors*
Th.Kubicki,K.Lübelsmeyer,J.Ortmanns,D.Pandoulas,O.Syben, M.Toporowsky,W.J.Xiao
Preprint PITHA 93/38 RWTH Aachen and
Nucl.Instr. and Meth. in Phys.Res. **A345** (1994), 468-473

[15] M.Rogalla, *Calculation of the electric field and charge collection in Schottky GaAs detectors*,
T.Kleindienst, *Particle simulation of ionising radiation detectors*,
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany.

[16] A.Castaldini et al., *Bias Dependence of the Depletion Layer Width in Semi-Insulating GaAs by Charge Collection Scanning Microscopy*,
Submitted to Scanning Microscopy, July 1994

[17] D.S.McGregor et al., *Fabrication and Evaluation of Room temperature Operated Radiation Detectors Processed from Undoped LEC Bulk Gallium Arsenide Material*,
Nucl.Instr. and Meth. in Phys.Res. **A322** (1992) 487;
D.S.McGregor et al., *Present status of undoped semi-insulating LEC bulk GaAs as a radiation spectrometer*,
Nucl.Instr. and Meth. in Phys.Res. **A343** (1994) 527-538

[18] M.L.Williams and I.J.Donnelly,
Studies of the Electric Field Distribution in Semi- Insulating GaAs and its Effects on Detector Performance,
6th Asia Pacific Physics Conference and 11th AIP Conference,
Griffith University, Brisbane, July 4-8, 1994, p 363

[19] F.Nava et al., *Influence of Electron Traps on Charge-Collection Efficiency in GaAs Radiation Detectors*,
CERN/LAA/94-09, CERN-PPE/94-50, 18th February, 1994 (submitted to N.I.M.);
L.Berluti et al., *Gallium arsenide particle detectors: a study of the active region and charge collection efficiency*
CERN preprint CERN/PPE/94-109

[20] M.Brozell, *Electric field observations in GaAs particle detectors*,
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany;
Semi-insulating GaAs and particle detectors,
Proc. of 20th Eloisatron Workshop on GaAs detectors and electronics for High Energy Physics, Erice 1992,
(World-Scientific, C.DelPapa, P.-G.Pelfer, K.M.Smith eds.)

[21] D.Alexiev, K.S.A.Butcher, M.Edmondson and T.L.Tansley,
Thermal Annealing of Liquid Phase Epitaxial Gallium Arsenide,
J. Crystal Growth **135** (1994) 367-369

[22] T.J.Sumner, S.M.Grant, D.Alexiev, and K.S.A.Butcher,
LPE GaAs as an X-Ray Detector for Astronomy,
Nucl. Instr. and Meth. in Phys. Res. (1994) (in press);

S.M.Grant, T.J.Sumner, J.P.Warren, D.Alexiev and K.S.A.Butcher,
Implications of Carrier Mobility Limitations for GaAs as an X-Ray Detector,
Proc. SPIE **2006** (1993) 41-51

[23] E.Bauser, *L.P.E. for GaAs Radiation Detectors,*
1st Int. Gallium Arsenide Workshop, February 1993, Joostal, Germany

[24] D.Alexiev, K.S.A.Butcher and J.W.Boldeman,
Neutron Damage Studies of Liquid Phase Epitaxial Gallium Arsenide and High Purity Silicon,
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany

[25] J.Matheson,*First results from a double-sided GaAs microstrip detector*
Proc. 3rd.International Conference on Position-Sensitive Detectors, London 1993

[26] S.D'Auria, *Development of biasing structures and AC-coupled detectors and related contacts,*
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany

[27] V.B.Chmill et al., *Radiation Resistans of GaAs Structures Based on $\pi - \nu$ Junction,*
ATLAS Internal Note INDET-NO-036, 3rd February, 1994

[28] C.DaVia et al., *A hybrid pixel detector for the readout of scinillating fibres,*
Contributed paper to I.C.H.E.P. - 94 Conference, Glasgow, 20-27th July, 1994

[29] R.Brenner et al.,
Measurement of the spatial resolution of double-sided, double-metal A.C.-coupled silicon microstrip detectors,
Nucl.Inst. and meth. in Phys.Res. **A326** (1993) 189

[30] *Viking, a CMOS low noise monolithic 128 channel front end for Si-strip detector readout*
O.Toker,S.Masciocchi,E.Nygard,A.Rudge,P.Weilhammer
Nucl.Instr.and Meth. in Phys.Res. **A340**, (1994) 572-579

[31] *Radiation Tests of GaAs-Detectors*
W.Braunschweig,K.Lübelsmeyer,J.Ortmanns,D.Pandoulas,O.Syben,
M.Toporowsky,B.Wittmer,W.J.Xiao
Preprint PITHA 94/39 RWTH Aachen in preparation

[32] A.Chilingarov, *Investigations of GaAs detector with BIPOLTEST read-out,*
ATLAS Internal Note, July 1994

[33] V.B.Chmill et al., *GaAs Detectors based on $\pi - \nu$ Structures,*
Nucl.Instr. and Meth. in Phys.Res. **A326**, (1993) 310

[34] R.Bates, private communication ;
A.Longoni et al., *Noise characterisation of GaAs detectors and electronics,*
2nd Int. Gallium Arsenide Workshop, March 7-10 1994, Joostal, Germany

[35] *Radiation and Cryogenic Test Results with a Monolithic GaAs Preamplifier in C-FET Technology*
D.DiBitonto,W.Karpinski,K.Lübelsmeyer,G.Pierschel, D.Pandoulas,C.Rente,K.Subhani, and F.Tenbusch
Preprint Pitha 94/06 RWTH Aachen

[36] K.McIlvaney, J.H.Marsh,J.S.Roberts and C.Button,
Evaluation of MQW structures for use in spatial light modulators,
17th International Conf. on GaAs and related compounds, Jersey 1990,
(published in *Inst. Phys. Conf. Series 112 (1990) 621-626* ;
S.D'Auria,J.H.Marsh,V.O'Shea,K.M.Smith and J.S.Roberts,

MQW Modulators for X-ray imaging,
Submitted to *Electronic Letters*

[37] *AlGaAs/GaAs SAM-Avalanche Photo Diode : An X-Ray Detector for Low Energy Photons*
J.Lauter,D.Protic,A.Forste,H.Luth
Preprint Institut fur Schicht-und Ionentechnik and Institut fur Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
to be published in NIM